



Hamilton, C. A., Lloyd, J., Barlow, N. L. M., Innes, J. B., Flecker, R., & Thomas, C. P. (2015). Late Glacial to Holocene relative sea-level change in Assynt, northwest Scotland, UK. *Quaternary Research*, 84(2), 214-222. <https://doi.org/10.1016/j.yqres.2015.07.001>

Peer reviewed version

License (if available):  
CC BY-NC-ND

Link to published version (if available):  
[10.1016/j.yqres.2015.07.001](https://doi.org/10.1016/j.yqres.2015.07.001)

[Link to publication record in Explore Bristol Research](#)  
PDF-document

This is the author accepted manuscript (AAM). The final published version (version of record) is available online via Elsevier at <http://www.sciencedirect.com/science/article/pii/S0033589415000721>. Please refer to any applicable terms of use of the publisher.

## University of Bristol - Explore Bristol Research

### General rights

This document is made available in accordance with publisher policies. Please cite only the published version using the reference above. Full terms of use are available:  
<http://www.bristol.ac.uk/red/research-policy/pure/user-guides/ebr-terms/>

1 **Late Glacial to Holocene relative sea level change in Assynt,**  
2 **northwest Scotland, UK**

3

4 Christine A. Hamilton<sup>1</sup>

5 Jeremy M. Lloyd <sup>1\*</sup>

6 Natasha L.M. Barlow<sup>1</sup>

7 James B. Innes<sup>1</sup>

8 Rachel Flecker<sup>2</sup>

9 Caleb P. Thomas<sup>2</sup>

10

11 \*Corresponding author. Email address: j.m.lloyd@durham.ac.uk Tel.: +44 (0) 191 33 41874

12 <sup>1</sup> Geography Department, Durham University, Durham, DH1 3LE, UK

13 <sup>2</sup> School of Geographical Sciences, University of Bristol, Bristol, BS8 1SS, UK

14

15 **Keywords**

16 Sea level; glacial isostatic adjustment; palaeoenvironmental reconstruction; Late Glacial

## 17    **Abstract**

18    Relative sea-level change (RSL), from the Late Glacial through to the late Holocene, is reconstructed for the  
19    Assynt region, northwest Scotland, based on bio- and lithostratigraphical analysis. Four new radiocarbon-  
20    dated sea-level index points help constrain RSL change for the Late Glacial to late Holocene. These new  
21    data, in addition to published material, capture the RSL fall during the Late Glacial and the rise and fall  
22    associated with the mid-Holocene highstand. Two of these index points constrain the Late Glacial RSL  
23    history in Assynt for the first time, reconstructing RSL falling from  $2.47 \pm 0.59$  m OD to  $0.15 \pm 0.59$  m OD at  
24    c. 14000 – 15000 cal. BP. These new data test model predictions of glacial isostatic adjustment (GIA),  
25    particularly during the early deglacial period which is currently poorly constrained throughout the British  
26    Isles. While the empirical data from the mid- to late-Holocene to present matches quite well with recent  
27    GIA model output, there is a relatively poor fit between the timing of the Late Glacial RSL fall and early  
28    Holocene RSL rise. This mismatch, which is also evident elsewhere in northwest Scotland, may result from  
29    uncertainties associated with both the global and local ice components of GIA models.

## 30    **Introduction**

31    The United Kingdom has been the focus of sea-level research for a number of decades (e.g. Tooley 1982;  
32    Devoy 1982; Shennan et al. 2005; Shennan et al. 2006a). The British and Irish Ice Sheet (BIIS) provides a  
33    compact case-study suitable for disentangling the relative contributions of eustasy, deformation of the  
34    ocean geoid, isostasy and local processes to regional records of post-Last Glacial Maximum (LGM) relative  
35    sea-level (RSL) change (Flemming, 1982; Shennan, 1989). The pattern of RSL change in Scotland is of  
36    particular interest as it is dominated by a complex spatial pattern of glacial isostatic adjustment (GIA)  
37    caused by the proximity of the centre of the LGM BIIS, and the peripheral effects of the Fennoscandian ice  
38    sheet (Peltier, 1998). As a consequence, post LGM records of RSL change in Scotland have the potential to  
39    refine, both the ice sheet history and Earth rheology components of GIA models. The Arisaig sea-level curve  
40    from western Scotland, which is currently the longest and most complete RSL archive for the British Isles  
41    (Shennan et al. 1996; Shennan et al. 2005), is a particularly important test of GIA models (e.g. Shennan et  
42    al. 2006a; Bradley et al. 2011). Many other locations, particularly those close to the centre of the LGM BIIS,  
43    currently have very limited records of past sea level, particularly covering the Late Glacial period, with  
44    spatially and temporally disparate sea level index points. The aim of this paper is to develop new records of  
45    past sea level for the understudied Assynt region of northwest Scotland (Figure 1), extending the current  
46    record, from Coigach (Shennan et al. 2000), beyond the mid-Holocene. Offshore geological records from  
47    northwest Scotland show that this region consisted of a series of LGM ice streams which channelled ice  
48    offshore towards the continental shelf off northwest Scotland (Stoker & Bradwell 2005; Bradwell et al.  
49    2007; Bradwell et al. 2008a; Bradwell 2008b). New sea level data from this region will contribute to refining  
50    the next generation of ice sheet and GIA models which have the potential to reconstruct dynamic ice sheet  
51    processes (Kuchar et al., 2012) at a time when trimlines, previously identified as indicators of maximum ice  
52    thickness (McCarroll et al., 1995; Ballantyne et al., 1998), are being reinterpreted as englacial thermal  
53    boundaries, constraining minimum ice elevation (Ballantyne and Hall, 2008; Ballantyne, 2010; Fabel et al.,  
54    2012).

## 55 Existing relative sea level data from northwest Scotland

56 Raised beaches, coastal geomorphology, buried peats and salt marshes have all been used to develop post-  
57 LGM and Holocene records of past sea level. The most widely employed approach in northwest Scotland  
58 involves isolation basins which, in this region of isostatic uplift, are preserved above current sea level and  
59 record phases of marine transgression and regression (e.g. Shennan et al. 1994; 1995a; 1995b; 1996; 1999;  
60 2000; 2005; 2006b; Selby & Smith 2007). The successful application of this approach in the Morar region of  
61 western Scotland, resulted in the reconstruction of a 16,000 year, near continuous RSL record at Arisaig  
62 (Figure 1A) (Shennan et al., 2005). By comparison, records further north typically comprise only a few  
63 Holocene data points limiting the interpretation of regional post LGM RSL change in northwest Scotland.  
64 Existing sea-level index points from the Assynt region are restricted to Coigach, 20 km northwest of  
65 Ullapool (Figure 2), and extend from the early through to the late Holocene (Shennan et al. 2000). Diatom,  
66 foraminifera and pollen assemblages preserved in sediment sequences from Dubh Lochan (isolation basin),  
67 Loch Raa (tidal marsh) and Badentarbet (wetland and barrier) (Figure 1A) indicate a RSL rise to a mid-  
68 Holocene highstand of c. 2.6 m OD followed by a RSL fall (Shennan et al. 2000). In addition, raised  
69 shorelines have been identified in the Assynt region at Achnahaird Bay (rock platform at c. 5.2 m OD)  
70 (Shennan et al. 2000) and Stoer Beach (raised beach at 6.47 m OD). Although the timing of these sea level  
71 highstands is unknown, the position of mean sea level can be reconstructed assuming fossil shore platforms  
72 and beaches such as these formed between Mean Tide Level (MTL) and Mean High Water Spring Tide  
73 (MHWST) (Shennan et al. 2000). This indicates a water level between 3.1-5.2 m OD at Achnahaird Bay and  
74 4.37-6.47 m OD at Stoer Beach. The altitudes of these raised platforms however contradicts the regional  
75 reconstructions of the Main Postglacial Shoreline (-2 m OD) and the Blairdrummond Shoreline (-2 m OD),  
76 determined from a Gaussian quadratic trend surface model of raised beaches around Scotland (Smith,  
77 2005). Salt marsh RSL records from Loch Laxford and Kyle of Tongue (Figure 1A) indicate a RSL fall in line  
78 with GIA models of late Holocene isostatic uplift in the region (Barlow et al., 2014).

## 79     **Study sites**

80     The Assynt region extends along the Scottish northwestern coastline from Loch Broom (Ullapool) to  
81     Eddrachillis Bay (Figure 1A). The fjordic landscape has been sculpted by past glacial cycles resulting in  
82     ‘knock-and-lochan’ topography, dominated by ice-scoured rock outcrop covered by peat and is well suited  
83     to lake-basin development (Lawson, 1995; Gillen, 2003). Sediment sequences from isolation basins at Duart  
84     Bog, Loch Duart Marsh and Oldany, on the north coast of the Assynt region (Figure 1A), were investigated  
85     in November 2013. Basins inundated during part of the tidal cycle accumulate brackish or marine  
86     sediments, whilst those above Highest Astronomical Tide (HAT) accumulate freshwater sediments; changes  
87     in sedimentary units correspond with the isolation or ingression of the basin therefore reflecting its  
88     position in relation to sea level (Lloyd, 2000; Lloyd and Evans, 2002). Duart Bog is located along the  
89     western shoreline of Loch Nedd, a sea loch (Figure 1B). This low-lying, sediment-filled basin is sheltered by  
90     surrounding deciduous woodland with steep topography of Lewisian Gneiss ascending to the south west of  
91     the basin. Loch Duart Marsh is accessed through the woodland encircling Duart Bog (Figure 1B) and is a  
92     small, largely infilled basin, c. 53 x 23 m with fringing salt marsh, connected to Loch Nedd at high tide via  
93     the adjacent tidal pond. A bedrock sill with overlying boulders, separates Loch Duart Marsh, at low tide,  
94     from the tidal pond which is also isolated from Loch Nedd during part of the tidal cycle. Oldany is a large  
95     infilled basin lying just below 10 m OD and sheltered by the surrounding steep topography of Lewisian  
96     Gneiss bedrock outcrop.

97

## 98     **Methods**

99     Methods follow established approaches to reconstructing past sea level from isolated basin sediments  
100     (Shennan et al., 2015). Gouge-coring transects across each basin documented stratigraphic changes and  
101     the depth of the basin’s sill, where buried. Sediments were logged using the Tröels-Smith (1955)  
102     descriptive scheme. Material was collected for laboratory analysis using a Russian corer, with the samples  
103     wrapped in plastic and stored in a fridge on return to Durham. Core location, altitudes and the elevation of  
104     each basin’s sill were surveyed using a Sokkia Set 6 Total Station and levelled to Ordnance Datum (m OD)

105 using the flush bracket benchmark 12125, located on the south side of Clashnessie Bridge (Figure 1A) (NC  
106 0557 3080).

107 Palaeoenvironmental reconstruction through cores from each basin is based upon diatom analysis,  
108 supported by pollen identification and sediment organic content. The strong relationship between diatom  
109 taxa and salinity accurately enables marine, brackish-water and freshwater phases of the isolation process  
110 to be characterised (Kolbe, 1927; Hustedt, 1953; Vos and De Wolf, 1988). Diatom sample preparation  
111 followed the standard method summarised by Palmer & Abbott (1986) and Battarbee (1986). An  
112 alternative methodology, designed by Scherer (1994) to determine the absolute abundances of diatoms,  
113 was used at the base of LDM-13-1 (200 cm to 220 cm) because of poor diatom preservation and a high clay  
114 content. This settling method produces slides with an even distribution of valves with minimal clumping  
115 (Maddison, 2005). A minimum of 250 valves were counted where possible with diatom species  
116 identification following Hustedt (1953), Hartley et al. (1996), Haworth (1976) and Robinson (1982). Species  
117 are grouped according to salt tolerance using the Halobian classification scheme (Kolbe, 1927; Hustedt,  
118 1953; Hemphill-Haley, 1993) and plotted as greater than 5 % of the total diatom valves counted, using C2  
119 (Juggins, 2003). Diatoms are zoned based on stratigraphically constrained cluster analysis using Tilia's  
120 constrained incremental sum of squares (CONISS) software (Grimm, 1987). Percentage loss on ignition (LOI)  
121 provides an indication of the organic content through the cores to complement the diatom analysis and is  
122 determined by combustion of material for 30 minutes at 850 °C following drying of the material at 105 °C  
123 overnight (Heiri et al., 2001).

124 AMS radiocarbon dating of bulk sediment samples from the organic unit adjacent to a palaeoenvironmental  
125 transition, as identified by the diatom assemblages, provides chronological control for the periods of  
126 marine ingression and regression. Radiocarbon measurements were conducted by the <sup>14</sup>C CHRONO Centre  
127 for Climate, the Environment, and Chronology and Beta Analytic and calibrated using CALIB REV7.0 and  
128 IntCal13 calibration curve (Reimer et al., 2013) with the 2 sigma age range reported in Table 1. Pollen  
129 analysis was used to complement the radiocarbon chronology. Pollen preparation followed the standard  
130 methodology outlined by Moore et al. (1991). Most of the pollen analysis is qualitative, for the purpose of

131 providing a relative age for the isolation and ingression contacts identified rather than for  
132 palaeoenvironmental reconstruction. Counts for qualitative analysis exceeded 66 grains. Full counts (100-  
133 200 grains) however are given for Duart Bog (index point 1) as the radiocarbon date for this index point is  
134 considered unreliable, and these are presented in Figure 5.

135

## 136 **Results**

137 *Duart Bog (58°14.70'N, 5°10.67'W): Sill altitude 4.77 m OD*

138 The lithostratigraphy at Duart Bog documents a transitional sediment sequence from clay (430 cm to 425  
139 cm) to silty clay (425 cm to 408 cm) overlain by organic limus (408 cm to 380 cm) and an upper peat unit  
140 (380 cm to surface; Figure 3). Three zones can be identified in the diatom assemblages in core DuB-13-3  
141 (Figure 3). Brackish species dominate at the base of the core (zone 1), indicating a marine influence in the  
142 basin during initial clay sedimentation probably via its connection with Loch Nedd (Figure 1B). There is an  
143 abrupt change in diatom flora to predominantly freshwater species at 425 cm, marking the zone 1-2  
144 boundary. This reflects a reduction in marine influence caused by isolation of the basin. This transition to  
145 freshwater conditions, which persist through zone 2 and 3, coincides with a change from clay to organic  
146 rich silty clay and an associated increase in organic content as suggested by the loss on ignition results  
147 (Figure 3). This is followed by a steady increase in organic content up-core. Pollen analysis above the zone  
148 1-2 boundary indicates that this regression at 425m probably dates to the early part of the Late Glacial  
149 Interstadial due to the dominance of *Empetrum*. AMS <sup>14</sup>C dating of the regressive contact constrains it to  
150 12580-12840 cal. BP, therefore reconstructing RSL fall to before the Loch Lomond Stadial (12.9 – 11.7 ka).

151

152 *Loch Duart Marsh (58°14.78'N, 5°10.79'W): Sill altitude 1.95 m OD*

153 Core LDM-13-1 from Loch Duart Marsh consists of four main sediment units: a lower silty clay unit (220 cm  
154 to 200 cm) overlain by an organic rich silty clay deposit (200 cm to 158 cm) where rootlets are abundant; a  
155 silty clay unit between 158 cm and 60 cm with a 10 cm thick shell layer (152 cm to 142 cm); and a gradual



156 transitional increase in organic material to the upper unit of modern salt marsh peat. The organic content  
157 increases from 4 to 41 %, between 220 cm and the surface, with minor peaks above the overall trend at  
158 164 cm (31 %) and 28 cm (72 %) (Figure 4).

159 Based on the diatom flora and lithostratigraphy seven zones were identified using CONISS. The diatom flora  
160 is dominated by marine species in zone 1, indicating marine influence in the basin at the base of the  
161 sequence. The transition to zone 2 is characterised by a shift in diatom flora to freshwater species,  
162 indicating a reduction in marine influence and isolation of the basin from the sea by 202 cm. An AMS  $^{14}\text{C}$   
163 date just above this isolation contact provides an age of 14610-15240 cal. BP indicating a Late Glacial age  
164 (Table 1). The age of this transition is supported by qualitative pollen analysis which identified *Artemisia*,  
165 *Cyperaceae*, *Poaceae* and *Empetrum* (Supplementary Table 1).

166 There is an abrupt change in the diatom flora at 158 cm from the freshwater assemblage of zone 4, to the  
167 mixed marine and freshwater flora in zone 5 (Figure 4). This transition is indicative of a marine ingress  
168 into the basin. Qualitative pollen analysis indicates this inundation dates to the early-mid Holocene and this  
169 is confirmed by the AMS  $^{14}\text{C}$  date immediately below the transition at 160 cm (9890-10180 cal. BP; Table 1).  
170 This dated contact therefore constrains the timing of the RSL rise during the earliest part of the Holocene.

171 Marine conditions persist through zones 5 and 6 until a gradual change from approximately 65 cm across  
172 the boundary between zone 6 and zone 7. This transition is characterised by a reduction in marine diatoms  
173 and an increase in freshwater species, though the assemblage is still mixed water flora (Figure 4). The AMS  
174  $^{14}\text{C}$  date above this transition at 40 cm (310-480 cal. BP) illustrates that this decline in marine influence  
175 occurred during the Late Holocene, constraining the RSL fall to present following the mid-Holocene  
176 highstand. The lithostratigraphy supports the diatom assemblage; increases in organic matter correspond  
177 with the isolation and partial isolation of the basin by 202 cm and 40 cm respectively whilst increases in the  
178 inorganic content correlates with periods of stronger marine influence.

179 *Oldany (58°14.47'N, 5°14.50'W): Sill altitude 8.10 m OD*

180 Coring at Oldany recovered organic sediment overlying bedrock at all locations. The depth of organic  
181 accumulation ranged from 2 m to 6.5 m. Diatom analysis demonstrates that a freshwater environment  
182 (Supplementary Figure 1), recorded by the dominance of oligohalobian-indifferent species and the  
183 occurrence of halophobous species, persists throughout the core. This indicates that MSL did not exceed 6  
184 m OD at Oldany (calculated as sill altitude minus the difference between MHWST and MTL:  $8.1 - 2.1 = 6$  m  
185 OD), providing a limiting altitude for post-LGM RSL in Assynt.

186

## 187 **Discussion**

188 The diatom flora and lithostratigraphy of the cores studied show clear fluctuations in RSL in the Assynt  
189 region. These changes in RSL have been dated using AMS  $^{14}\text{C}$  and pollen stratigraphy to allow the  
190 generation of four sea-level index points (Table 2). The new index points, along with published data from  
191 Coigach, allow the generation of a new RSL curve for the Assynt area (Figure 6). The significance of this new  
192 sea-level curve is discussed in detail in the following sections.

193

### 194 *Post-Last Glacial Maximum relative sea-level change in Assynt*

195 The new sea-level index points (Table 2) from Duart Bog (index point 1) and Loch Duart Marsh (index point  
196 2) extend the published RSL record from Assynt (Shennan et al. 2000) back to the Late Glacial (Figure 6).  
197 The new limiting elevation from Oldany, where the freshwater diatom assemblage suggests the marine  
198 limit following regional post-LGM ice retreat was less than +6 m OD, also constrains the altitude of Late  
199 Glacial RSL (Figure 6). This is compatible with the altitude of raised shorelines in the Assynt region (Shennan  
200 et al. 2000). The sea level index points from Coigach (Shennan et al. 2000) and the new points from Duart  
201 provide constraints on the post-glacial- Holocene RSL.

Loch Duart Marsh index point 2 (negative tendency) constrains RSL to  $-0.15 \pm 0.59$  m OD at 14610-15240 cal. BP, an age supported by the pollen flora (Supplementary Table 1). A Late Glacial fall in sea level is also supported by index point 1 (negative tendency) from Duart Bog. However the chronological control from Duart Bog is less well constrained. Duart Bog (index point 1; negative tendency) places RSL at  $+2.47 \pm 0.59$  m OD and is radiocarbon dated to 12580-12840 cal. BP. However, this age is not supported by the pollen data close to the regressive contact at 425 cm, which suggests the index point is considerably older (Figure 5). Discrepancies between the relative elevation of the Loch Duart Marsh and Duart Bog sites also suggest that the radiocarbon date for index point 1 may be erroneously young. For example, if the index point 1 radiocarbon date were to be correct, a 2.82 m rise in RSL would be required following the isolation of Loch Duart Marsh and before the isolation of Duart Bog (Figure 6) due to differences in sill altitude for each site. Of the two sites, Loch Duart Marsh is at a lower altitude and therefore should record two marine intervals at the base of the core, rather than one, if the radiocarbon date for index point 1 was correct (Figure 4). Equally, because of the difference in elevation, Duart Bog should record the regression earlier than Loch Duart Marsh, rather than later, if both basins are recording the same RSL fall (Figure 6). The most likely explanation for these discrepancies is that the AMS  $^{14}\text{C}$  date from the Duart Bog core is incorrect, contaminated by younger carbon, sourced perhaps from the downward reworking of humic acid or rootlets (Balesdent, 1987). As the radiocarbon date for the regression contact at Duart Bog seems younger than expected based upon its elevation relative to Loch Duart Marsh, full pollen percentage counts were made above the regressive contact at 425 cm (Figure 5). Counts from 418.5 and 415 cm are dominated by *Empetrum*, with lesser frequencies of Cyperaceae and *Artemisia*. At 408.5 cm, however, Cyperaceae has become the most abundant pollen taxon, with reduced *Empetrum* and increased *Rumex*. Pollen analysis at nearby Lochan an Druim, 37 km north east at Eriboll (Birks, 1984), and elsewhere in northern Scotland (Pennington et al., 1972), has identified similar *Empetrum*-dominated pollen zones near the start of the Late Glacial Interstadial, followed by an analogous switch to Cyperaceae (Supplementary Figure 2). The *Empetrum* pollen zone in northern Scotland associated with the Late Glacial Interstadial, like the Duart Bog sample, is also dominated by sedge pollen. The virtual absence of *Juniperus* in the Duart Bog samples is also very similar to the early Interstadial data from Lochan an Druim, and means that these Duart Bog levels

cannot equate to late Loch Lomond Stadial/early Holocene age, when *Juniperus* was abundant locally. By analogy with the pollen and radiocarbon data from Lochan an Druim, therefore, the Duart Bog pollen must indicate a time early in the Lateglacial Interstadial, by interpolation about c.14,400 cal. BP (Supplementary Figure 2). This demonstrates that the  $^{14}\text{C}$  date for index point 1 is erroneously young. The regression visible at the base of the Duart Bog core is therefore likely to be similar to index point 2 recorded in the Loch Duart Marsh core.

Sea-level index points from both Loch Duart Marsh (index point 3) and Coigach (Shennan et al. 2000) provide constraint on the RSL rise before the mid-Holocene highstand (Figure 6). The new index point from Loch Duart Marsh shows that RSL rose earlier than previously thought to -0.15 m OD at 9890-10180 cal. BP (Figure 6). Based on the index points from Coigach, sea level then rose to above 2.17 m OD at 8250-8370 cal. BP (Shennan et al. 2000). Freshwater diatom and pollen flora from Loch Raa, Coigach provides a limiting altitude for the mid-Holocene highstand at 2.6 m OD (Shennan et al. 2000). The persistence of freshwater conditions following the marine ingression at the base of DuB-13-3 supports this by providing a further limiting point, constraining the altitude of the mid-Holocene highstand to below  $+2.47 \pm 0.59$  m OD. Following the mid-Holocene highstand, a series of index points from Coigach (Shennan et al. 2000) constrain a RSL fall (Figure 6). Index point 4 which marks the onset of Loch Duart Marsh isolation provides a further constraint on this falling sea level with a RSL of  $+1.05 \pm 1.21$  m OD, between 310 -480 cal. BP. This index point is compatible with recent records of RSL change from salt marshes at Loch Laxford and Kyle of Tongue (18 km and 49 km north east of Duart respectively), which indicate a gradual fall in RSL over the last 2000 years in northwest Scotland (Barlow et al., 2014).

249

#### Fit with glacial isostatic adjustment models

By extending the existing RSL curve for the Assynt region back to the Late Glacial it is now possible to compare recent GIA model outputs for the region with data from both the earlier part of the deglacial sequence and the late Holocene. There is a clear mismatch with the Bradley et al. (2011) GIA model output

254 during the Late Glacial, as the model under predicts the sea-level elevation recorded at Duart Bog and Loch  
255 Duart Marsh by over 10 m (Figure 6). Some of this discrepancy (c. 2 m) may be resolved by adopting the  
256 palaeo-tidal correction modelled for MHWST by Neill et al. (2010) for Arisaig. Changes in tidal amplitude,  
257 since the LGM, have rarely been taken into account despite the significant impact on the interpretation of  
258 isolation basin records. Neill et al. (2010), however, predicted that MHWST has decreased by 2.6 m since 16  
259 ka, with around 2 m of this decline occurring during the Late Glacial period.

260 The marine limit elevation, from Oldany (6 m OD), as well as the raised shoreline evidence from the wider  
261 Assynt region, fits reasonably well with the Bradley et al. (2011) model prediction of maximum post LGM  
262 sea level of c. 5 m OD (Shennan et al. 2000). Although these geomorphological features are not dated,  
263 comparison with the age-constrained index points indicates that they are too high to be mid-Holocene in  
264 age and are therefore likely to be a result of Late Glacial sea level. Reconstructions of RSL at both Duart  
265 (index point 3) and Coigach, lie over 5 m above the Bradley et al. (2011) model prediction of rising RSL prior  
266 to the mid-Holocene highstand, while index points constraining the mid-Holocene highstand itself (from  
267 Coigach (Shennan et al. 2000)) and the late Holocene RSL fall (from Duart-index point 4), are close to that  
268 predicted by the Bradley et al. (2011) model.

269 The Kuchar et al. (2012) GIA model combined a 3-D thermomechanical ice sheet model (Hubbard et al.,  
270 2009) with the Bradley et al. (2011) GIA Earth model. The Hubbard et al. (2009) ice model is driven by  
271 palaeoclimate data based on the physics of ice flow; it therefore provides a test for the interpretation of  
272 trimline data (e.g. Ballantyne & Hall 2008; Ballantyne 2010). The Kuchar et al. model prediction for the  
273 Assynt region (Figure 6) is based on the minimal ice reconstruction of the Hubbard et al. (2009) ice model.  
274 The Kuchar et al. (2012) model produces a larger isostatic response and its prediction for Arisaig fits  
275 extremely well with the RSL data from this site, in contrast with previous models (e.g. Shennan et al. 2006a;  
276 Bradley et al. 2011). Similarities between Assynt's vertical ice extent reconstructed by the Kuchar et al.  
277 (2012) model and that deduced from the region's weathering limits for the Bradley et al. (2011) ice model  
278 leads to these GIA models producing relatively similar RSL predictions from ~15 k yr BP to present (within  
279 ~1 m) (Figure 6). The region's vertical ice extent determined from weathering limits on Ben More Assynt,

280 Conival and Canisp, for example, ranges from around 750 to 850 m (Ballantyne, 1997; McCarroll et al.,  
281 1995), greater than that reconstructed by the Kuchar et al. (2012) minimal ice model (500 to 750 m thick).  
282 Consequently, whilst the Kuchar et al. (2012) predictions produce a good fit for Arisaig, this is not the case  
283 for Assynt where the reconstructed vertical ice extent appears too conservative.

284

#### 285 *Relative sea level in northwest Scotland and implications for models of the British and Irish Ice Sheet*

286 The combination of ice and Earth models adopted by Bradley et al. (2011) for the British Isles results in  
287 good model-data fit for the Holocene part of the 16000 year Arisaig RSL record (Shennan et al. 2005),  
288 though the model struggles to fit the oldest and highest data points. By comparison, the additional ice  
289 thickness in Hubbard et al. (2009) adopted in the Kuchar et al. (2012) GIA model (with similar Earth model  
290 parameters to Bradley et al. (2011)) provides better fit with the oldest part of the Arisaig curve. However,  
291 our new data supports the assertion (as noted by Kuchar et al. 2012) that despite additional ice thickness in  
292 the Hubbard et al. (2009) ice model over the central region, there is still poor GIA model and RSL data fit in  
293 the far northwest of Scotland during the Late Glacial and early-Holocene. The consistency of Earth model  
294 solutions (e.g. Lambeck et al. 1998; Steffen & Kaufmann 2005; Bradley et al. 2011; Kuchar et al. 2012)  
295 suggests that the misfit is most likely a consequence of the ice model: either the global melt history or  
296 underestimation of local ice thickness.

297 Resolving the exact timing of Antarctic melt remains a challenge (Peltier, 1998; Peltier et al., 2002; Shennan  
298 et al., 2002; Whitehouse et al., 2012). Many recent far-field RSL investigations have sought to resolve the  
299 post-LGM ‘eustatic’ record, but uncertainties associated with local processes, e.g. depositional lowering  
300 and tectonic movements in far field locations, are not always fully understood and/or quantified (e.g. Zong  
301 2004; Horton et al. 2005; Bradley et al. 2011; Deschamps et al. 2012). Consequently, data-model misfit in  
302 northwest Scotland may be a consequence of uncertainties in the global ice model. However, as much of  
303 the misfit is during the Late Glacial, it suggests the errors may primarily be associated with the ‘local’ ice  
304 model during a time when regional isostatic processes are the most dominant component of RSL change.

Recent reassessment of palaeo-trimline data in Scotland (e.g. McCarroll et al. 1995; Ballantyne et al. 1998), based on cosmogenic-nuclide analysis of bedrock and erratic ‘pairs’, has resulted in their reinterpretation as englacial thermal boundaries. These features therefore, are now thought to constrain the minimum rather than maximum surface elevation of the BIIS (Ballantyne & Hall 2008; Ballantyne 2010; Fabel et al. 2012), resulting in greater ice thicknesses than in the Brooks et al (2008) ice model used by Bradley et al., (2011). This reassessment is supported by the improved fit between the deglacial RSL data from central western Scotland (for example Arisaig) and the Kuchar et al. (2012) GIA model which contains much thicker ice. However, the Kuchar et al. (2012) minimal ice model (as preferred for Arisaig) still contains LGM ice 100 m thinner than that deduced from the weathering limits in the northern sector of the ice sheet (e.g. Assynt) (McCarroll et al., 1995; Ballantyne, 1997). The reinterpreted field data constraining ice thickness and the Assynt RSL curve, suggest that the regional BIIS ice model used by Bradley et al. (2011) and Kuchar et al. (2012) is still too conservative in this region and points to the local ice model being the most likely cause of the underestimation of modelled height of RSL in Assynt (Figure 6). The issue of ice thickness and it’s underestimation is not exclusive to the Scottish sector of the BIIS as similar misfits have been observed elsewhere , such as Ireland (e.g. Brooks et al. 2008; Kuchar et al. 2012).

Increased ice thickness estimates may also be complemented with improved deglacial chronologies. Cosmogenic  $^{10}\text{Be}$  dating is extensively used to estimate the timing of deglaciation and glacial readvances, as well as reconstructions of the BIIS extent. Improvements in cosmogenic dating have resulted in a shift to the use of locally determined  $^{10}\text{Be}$  production rates (LPR), rather than global  $^{10}\text{Be}$  production rates which have refined the deglaciation chronology (Balco et al., 2008; Ballantyne, 2012; Ballantyne and Stone, 2012; Ballantyne et al., 2013). For example, Ballantyne (2012) recalibrated existing exposure ages using LPR for sites extending from Orkney to Beinn Inverveigh in the Scottish Highlands. Prior to recalibration, 62 % of these published  $^{10}\text{Be}$  exposure ages for Loch Lomond Stadial ice retreat were younger than 11.7 ka. Following recalibration, 73% were within the chronological limits of the Loch Lomond Stadial (12.9-11.7 ka) (Ballantyne 2012). Revising the deglaciation chronology, based on the recalibration of erroneously young exposure ages, may also help reconcile the misfit between GIA models and the empirical data from northwest Scotland.

333 **Conclusions**

334 This paper presents new sea-level data for Assynt, northwest Scotland, which adds to the existing RSL data  
335 from Coigach (Shennan et al. 2000), extending the regional RSL curve back to the Late Glacial. There is good  
336 fit between the data and the GIA models of Kuchar et al. (2012) and Bradley et al. (2011) for the mid to  
337 late-Holocene; however, both models underestimate the elevation of RSL during the Late Glacial and early  
338 Holocene. Recent reassessment of trimline data has led to their interpretation as indicating the minimum  
339 surface elevation of the BIIS rather than maximum elevation (e.g. Ballantyne & Hall 2008; Ballantyne 2010).  
340 The RSL results from Assynt support this, suggesting the GIA models need to incorporate thicker ice in the  
341 northwest sector of the BIIS. Additional RSL index points from around the marine limit (c. 4-6 m) and the  
342 sea-level lowstand (c. 11-14 k yr BP) are needed to help further constrain the regional RSL history. This in  
343 turn needs to be complemented with new models of the BIIS ice sheet which include improved deglacial  
344 chronologies and estimates of ice sheet thickness.



## 345    **Acknowledgements**

346    We gratefully acknowledge funding from the Quaternary Research Association (AMS radiocarbon dating for  
347    three of the four sea-level index points) and the Department of Geography at Durham University (fieldwork  
348    costs). The Assynt Crofters Trust and Anna Barratt provided access to the study sites at Duart and Oldany  
349    respectively. We are grateful to Christopher Dias for his help during fieldwork and Ed Garrett for useful  
350    discussions concerning diatom identification. Support from the laboratory technicians in the Geography  
351    Department at Durham University as well as Dr Simon Cobb from the School of Geographical Sciences at  
352    the University of Bristol was appreciated. We would also like to thank Glenn Milne for supplying the model  
353    predictions used in Figure 6. We thank Ian Shennan and Jason Kirby for their helpful and constructive  
354    feedback on this research as well as Robin Edwards and an anonymous reviewer whose comments  
355    improved this manuscript.

## References

- Balco, G., Stone, J.O., Lifton, A., Dunai, T.J., 2008. A complete and easily accessible means of calculating surface exposure ages or erosion rates from  $^{10}\text{Be}$  and  $^{26}\text{Al}$  measurements. *Quaternary Geochronology* 3, 174–195.
- Balesdent, J., 1987. The turnover of soil organic fractions estimated by radiocarbon dating. *The Science of the Total Environment* 62, 405–408.
- Ballantyne, C., Hall, A., 2008. The altitude of the last ice sheet in Caithness and east Sutherland, northern Scotland. *Scottish Journal of Geology* 44, 169–181.
- Ballantyne, C.K., 2012. Chronology of glaciation and deglaciation during the Loch Lomond (Younger Dryas) Stade in the Scottish Highlands: implications of recalibrated  $^{10}\text{Be}$  exposure ages. *Boreas* 41, 513–526.
- Ballantyne, C.K., 2010. Extent and deglacial chronology of the last British-Irish Ice Sheet: implications of exposure dating using cosmogenic isotopes. *Journal of Quaternary Science* 25, 515–534.
- Ballantyne, C.K., 1997. Periglacial trimline in the Scottish Highlands. *Quaternary International* 38/39, 119–136.
- Ballantyne, C.K., McCarroll, D., Nesje, A., Dahl, S.O., Stone, J.O., 1998. The Last Ice Sheet in North-West Scotland: Reconstruction and Implications. *Quaternary Science Reviews* 17, 1149–1184.
- Ballantyne, C.K., Rinterknecht, V., Gheorghiu, D.M., 2013. Deglaciation chronology of the Galloway Hills Ice Centre, southwest Scotland. *Journal of Quaternary Science* 28, 412–420.
- Ballantyne, C.K., Stone, J.O., 2012. Did large ice caps persist on low ground in North-west Scotland during the Lateglacial Interstade? *Journal of Quaternary Science* 27, 297–306.
- Barlow, N.L.M., Long, A.J., Saher, M.H., Gehrels, W.R., Garnett, M.H., Scaife, R.G., 2014. Salt-marsh reconstructions of relative sea-level change in the North Atlantic during the last 2000 years. *Quaternary Science Reviews* 99, 1–16.
- Battarbee, R., 1986. Diatom Analysis, in: Berglund, B. (Editor), *Handbook of Holocene Palaeoecology and Palaeohydrology*. Wiley, Chichester, pp. 527–570.
- Birks, H., 1984. Late-Quaternary pollen and plant macrofossil stratigraphy at Lochan An Druim, north-west Scotland, in: Haworth, E.Y., Lund, J.W. (Editors), *Lake Sediments and Environmental History*. University of Minnesota Press, Minneapolis, pp. 377–404.
- Bradley, S.L., Milne, G. a., Shennan, I., Edwards, R., 2011. An improved glacial isostatic adjustment model for the British Isles. *Journal of Quaternary Science* 26, 541–552.
- Bradwell, T., Stoker, M., Golledge, N.R., Wilson, C.K., Merritt, J.W., Long, D., Everest, J.D., Hestvik, O.B., Stevenson, A.G., Hubbard, A.L., Finlayson, A.G., Mathers, H.E., 2008a. The northern sector of the last British Ice Sheet: Maximum extent and demise. *Earth-Science Reviews* 88, 207–226.
- Bradwell, T., Stoker, M., Krabbendam, M., 2008b. Megagrooves and streamlined bedrock in NW Scotland: The role of ice streams in landscape evolution. *Geomorphology* 97, 135–156.
- Bradwell, T., Stoker, M., Larter, R., 2007. Geomorphological signature and flow dynamics of The Minch palaeo-ice stream, northwest Scotland. *Journal of Quaternary Science* 22, 609–617.
- Brooks, A., Bradley, S., Edwards, R., Milne, G., Horton, B., Shennan, I., 2008. Postglacial relative sea-level observations from Ireland and their role in glacial rebound modelling. *Journal of Quaternary Science* 23, 175–192.
- Deschamps, P., Durand, N., Bard, E., Hamelin, B., Camoin, G., Thomas, A.L., Henderson, G.M., Okuno, J., Yokoyama, Y., 2012. Ice-sheet collapse and sea-level rise at the Bolling warming 14,600 years ago. *Nature* 483, 559–564.
- Devoy, R.J., 1982. Analysis of the geological evidence for Holocene sea-level movements in southeast England. *Proceedings of the Geologists' Association* 93, 65–90.
- Fabel, D., Ballantyne, C.K., Xu, S., 2012. Trimlines, blockfields, mountain-top erratics and the vertical dimensions of the last British-Irish Ice Sheet in NW Scotland. *Quaternary Science Reviews* 55, 91–102.
- Flemming, N.C., 1982. Multiple regression analysis of earth movements and eustatic sea-level change in the United Kingdom in the past 9000 years. *Proceedings of the Geologists' Association* 93, 113–125.
- Gillen, C., 2003. *Geology and landscapes of Scotland*. Terra Publishing, Harpenden.
- Grimm, E., 1987. CONISS: a FORTRAN 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. *Computers and Geosciences* 13, 13–35.
- Hartley, B., Barber, H., Carter, J., 1996. *An Atlas of British Diatoms*. Biopress Limited, Bristol.

- Haworth, E.Y., 1976. The Changes in the Composition of the Diatom Assemblages Found in the Surface Sediments of Blelham Tarn in the English Lake District During 1973. *Annals of Botany* 40, 1195–1205.
- Heiri, O., Lotter, A., Lemcke, G., 2001. Loss on ignition as a method for estimating organic and carbon content in sediments: reproducibility and comparability of results. *Journal of Paleolimnology* 25, 101–110.
- Hemphill-Haley, E., 1993. Taxonomy of recent and fossil (Holocene) diatoms (Bacillariophyta) from northern Willapa Bay, Washington. US Geological Survey Open File Report 93-289, 1–151.
- Horton, B.P., Edwards, R.J., Lloyd, J.M., 2000. Implications of a microfossil transfer function in Holocene sea-level studies, in: Shennan, I., Andrews, J.E. (Editors), *Holocene Land-Ocean Interaction and Environmental Change around the North Sea*. Geological Society, Special Publication 166(1), London, pp. 41–54.
- Horton, B.P., Gibbard, P.L., Milne, G.M., Morley, R.J., Purintavaragul, C., Stargardt, J.M., 2005. Holocene sea levels and palaeoenvironments, Malay-Thai Peninsula, southeast Asia. *The Holocene* 15, 1199–1213.
- Hubbard, A., Bradwell, T., Golledge, N., Hall, A., Patton, H., Sugden, D., Cooper, R., Stoker, M., 2009. Dynamic cycles, ice streams and their impact on the extent, chronology and deglaciation of the British–Irish ice sheet. *Quaternary Science Reviews* 28, 758–776.
- Hustedt, F., 1953. Die Systematik der Diatomeen in ihren Beziehungen zur Geologie und Ökologie nebst einer Revision des Halobien-systems. *Svensk Botanisk Tidskrift* 47, 509–519.
- Juggins, S., 2003. C2 User guide. Software for ecological and palaeoecological data analysis and visualisation. University of Newcastle, Newcastle Upon Tyne.
- Kolbe, R., 1927. Zur Ökologie, Morphologie und Systematik der Brackwasser-Diatomeen. *Pflanzenforschung* 7, 1–146.
- Kuchar, J., Milne, G., Hubbard, A., Patton, H., Bradley, S., Shennan, I., Edwards, R., 2012. Evaluation of a numerical model of the British-Irish ice sheet using relative sea-level data: implications for the interpretation of trimline observations. *Journal of Quaternary Science* 27, 597–605.
- Lambeck, K., Smither, C., Johnston, P., 1998. Sea-level change, glacial rebound and mantle viscosity for northern Europe. *Geophysical Journal International* 134, 102–144.
- Lawson, T.J., 1995. The Quaternary of Assynt and Coigach: Field Guide, The Quaternary of Assynt and Coigach. Quaternary Research Association, Cambridge.
- Lloyd, J.M., 2000. Combined foraminiferal and thecamoebian environmental reconstruction from an isolation basin in NW Scotland: Implications for sea-level studies. *Journal of Foraminiferal Research* 30, 294–305.
- Lloyd, J.M., Evans, J.R., 2002. Contemporary and fossil foraminifera from isolation basins in northwest Scotland. *Journal of Quaternary Science* 17, 431–443.
- Maddison, E.J., 2005. Seasonally laminated late Quaternary Antarctic sediments. PhD thesis, Cardiff University.
- McCarroll, D., Ballantyne, C.K., Nesje, A., Dahl, S.-O., 1995. Nunataks of the last ice sheet in northwest Scotland. *Boreas* 24, 305–323.
- Moore, P., Webb, J., Collinson, M., 1991. *Pollen Analysis*, 2nd ed. Blackwell Scientific Publications, Oxford.
- Neill, S.P., Scourse, J.D., Uehara, K., 2010. Evolution of bed shear stress distribution over the northwest European shelf seas during the last 12,000 years. *Ocean Dynamics* 60, 1139–1156.
- Palmer, A., Abbott, W., 1986. Diatoms as indicators of sea-level change, in: van de Plassche, O. (Editor), *Sea-Level Research: A Manual for the Collection and Evaluation of Data*. Geo books, Norwich.
- Peltier, W.R., 1998. Postglacial variations in the level of the sea: Implications for climate dynamics and solid-earth geophysics. *Reviews of Geophysics* 36, 603–689.
- Peltier, W.R., Shennan, I., Drummond, R., Horton, B., 2002. On the postglacial isostatic adjustment of the British Isles and the shallow viscoelastic structure of the Earth. *Geophysical Journal International* 148, 443–475.
- Pennington, W., Haworth, E., Bonny, A., Lishman, J., 1972. Lake Sediments in northern Scotland. *Philosophical Transactions of the Royal Society B: Biological Sciences* 264, 191.
- Preuss, H., 1979. Progress in computer evaluation of sea-level data within the IGCP project no. 61, in: Flexor, I. (Editor), *International Symposium on Coastal Evolution in the Quaternary*. Sao-Paulo, Brazil, pp. 104–134.

- Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Cheng, H., Edwards, R.L., Freidrich, M., Grootes, P.M., Guilderson, T.P., Hafliðason, H., Hajdas, I., Hatt, A.C., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., Manning, S.W., Niu, M., Reimer, R.W., Richards, D.A., Scott, E.M., Southon, J.R., Turney, C.S.M., van der Plicht, J., 2013. IntCal13 and Marine13 radiocarbon age calibration curves 0-50000 years cal BP. *Radiocarbon* 55, 1869–1887.
- Robinson, M., 1982. Diatom Analysis of Early Flandrian Lagoon Sediments from East Lothian, Scotland. *Journal of Biogeography* 9, 207–221.
- Scherer, R.P., 1994. A new method for the determination of absolute abundance of diatoms and other silt-sized sedimentary particles. *Journal of Paleolimnology* 12, 171–179.
- Selby, K.A., Smith, D.E., 2007. Late Devensian and Holocene relative sea-level changes on the Isle of Skye, Scotland, UK. *Journal of Quaternary Science* 22, 119–139.
- Shennan, I., 1989. Holocene crustal movements and sea-level changes in Great Britain. *Journal of Quaternary Science* 4, 77–89.
- Shennan, I., Innes, J.B., Long, A.J., Zong, Y., 1994. Late Devensian and Holocene relative sea-level changes at Loch nan Eala, near Arisaig, northwest Scotland. *Journal of Quaternary Science* 9, 261–283.
- Shennan, I., Innes, J.B., Long, A.J., Zong, Y., 1995a. Holocene relative sea-level changes and coastal vegetation history at Kentra Moss, Argyll, northwest Scotland. *Marine Geology* 124, 43–59.
- Shennan, I., Innes, J.B., Long, A.J., Zong, Y., 1995b. Late Devensian and Holocene relative sea-level changes in Northwestern Scotland: New data to test existing models. *Quaternary International* 26, 97–123.
- Shennan, I., Green, F., Innes, J., Lloyd, J., Rutherford, M., Walker, K., 1996. Evaluation of Rapid Relative Sea-Level Changes in North-West Scotland During the Last Glacial- Interglacial Transition: Evidence from Ardtoe and Other Isolation Basins. *Journal of Coastal Research* 12, 862–874.
- Shennan, I., Tooley, M., Green, F., Innes, J., Kennington, K., Lloyd, J., Rutherford, M., 1999. Sea level, climate change and coastal evolution in Morar, northwest Scotland. *Geologie en Mijnbouw* 77, 247–262.
- Shennan, I., Lambeck, K., Horton, B., Innes, J., Lloyd, J., McArthur, J., Purcell, T., Rutherford, M., 2000. Late Devensian and Holocene records of relative sea-level changes in northwest Scotland and their implications for glacio-hydro-isostatic modelling. *Quaternary Science Reviews* 19, 1103–1135.
- Shennan, I., Peltier, W., Drummond, R., Horton, B., 2002. Global to local scale parameters determining relative sea-level changes and the post-glacial isostatic adjustment of Great Britain. *Quaternary Science Reviews* 21, 397–408.
- Shennan, I., Hamilton, S., Hillier, C., Woodroffe, S., 2005. A 16000-year record of near-field relative sea-level changes, North-west Scotland, United Kingdom. *Quaternary International* 133-134, 95–106.
- Shennan, I., Bradley, S., Milne, G., Brooks, A., Bassett, S., Hamilton, S., 2006a. Relative sea-level changes, glacial isostatic modelling and ice-sheet reconstructions from the British Isles since the Last Glacial Maximum. *Journal of Quaternary Science* 21, 585–599.
- Shennan, I., Hamilton, S., Hillier, C., Hunter, A., Woodall, R., Bradley, S., Milne, G., Brooks, A., Bassett, S., 2006b. Relative sea-level observations in western Scotland since the Last Glacial Maximum for testing models of glacial isostatic land movements and ice sheet reconstructions. *Journal of Quaternary Science* 21, 601–613.
- Shennan, I., Long, A.J., Horton, B.P., 2015. *Handbook of Sea-Level Research*. Wiley-Blackwell, Chichester.
- Smith, D.E., 2005. Evidence for Secular Sea Surface Level Changes in the Holocene Raised Shorelines of Scotland, UK. *Journal of Coastal Research* 42, 26–42.
- Steffen, H., Kaufmann, G., 2005. Glacial isostatic adjustment of Scandinavia and northwestern Europe and the radial viscosity structure of the Earth's mantle. *Geophysical Journal International* 163, 801–812.
- Stoker, M., Bradwell, T., 2005. The Minch palaeo-ice stream, NW sector of the British-Irish Ice Sheet. *Journal of the Geological Society* 162, 425–428.
- Tooley, M.J., 1982. Sea-level changes in northern England. *Proceedings of the Geologists' Association* 93, 43–51.
- Tröels-Smith, J., 1955. Characterisation of Unconsolidated Sediments. *Danmarks Geologiske Undersogelse Series IV*, 38–73.
- Vos, P.C., De Wolf, H., 1988. Methodological aspects of paleo-ecological diatom research in coastal areas of the Netherlands. *Geologie en Mijnbouw* 67, 31–40.

- Whitehouse, P.L., Bentley, M.J., Milne, G. a., King, M. a., Thomas, I.D., 2012. A new glacial isostatic adjustment model for Antarctica: calibrated and tested using observations of relative sea-level change and present-day uplift rates. *Geophysical Journal International* 190, 1464–1482.
- Zong, Y., 2004. Mid-Holocene sea-level highstand along the Southeast Coast of China. *Quaternary International* 117, 55–67.

**Table 1:** New radiocarbon dates from the Duart area of Assynt from this study.

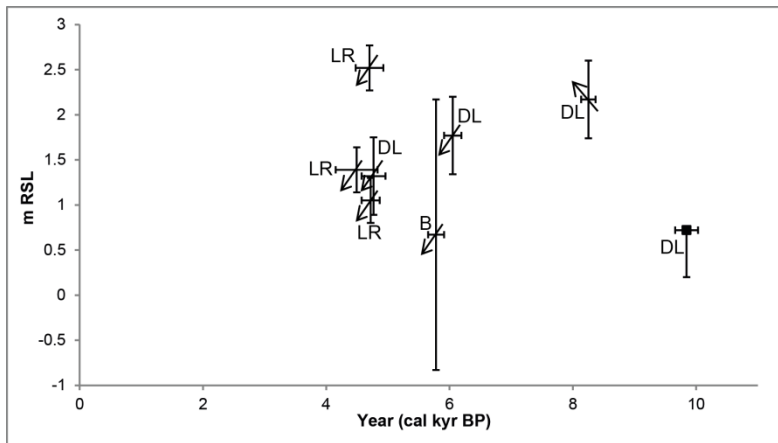
Site (index point #)	Laboratory code	<sup>14</sup> C age BP (± 2σ)	Calibrated age (cal. BP)	Altitude (m OD)	Material dated/Comment
Duart Bog (1)	UBA-26502	10810 ± 82	12580 – 12840	2.52	Organics within silt clay unit, above regressive contact
Loch Duart Marsh (2)	Beta-390107	12670 ± 80	14610 – 15240	0.03	Organics within organic rich silty clay unit, above regressive contact
Loch Duart Marsh (3)	UBA-26501	8887 ± 72	9890 - 10180	0.46	Organics within organic rich silty clay unit, below transgressive contact and away from shell layer (142 cm to 152 cm)
Loch Duart Marsh (4)	UBA-26500	332 ± 68	310 - 480	1.66	Organics within limus regressive unit

**Table 2:** Sea-level index points for the Assynt region from Duart (this paper) and Coigach (Shennan et al. (2000)). Dating associated with Duart Bog (1\*) is based on pollen evidence rather than radiocarbon material (presented in Table 1). The positive (+) or negative (-) tendency is noted for each index point whilst limiting index points (L) are also highlighted. The vertical error associated with each sea-level index point presented for Duart was determined as follows  $\sqrt{e_1^2 + e_2^2 + e_3^2 \dots + e_n^2}$ , where  $e_1 \dots e_n$  are the individual sources of error (Preuss 1979; Shennan et al. 2000; Horton et al. 2000). Errors associated with levelling (index point 1-4: 0.1 m), sill elevation (index point 2-4: 0.05 m) and indicative range (index point 1-3: 0.58 m; 4: 1.20 m) were taken into account. In addition the impact of sediment compaction (0.04 m) was determined for the upper regressive sequence of LDM 13-1 associated with index point 4.

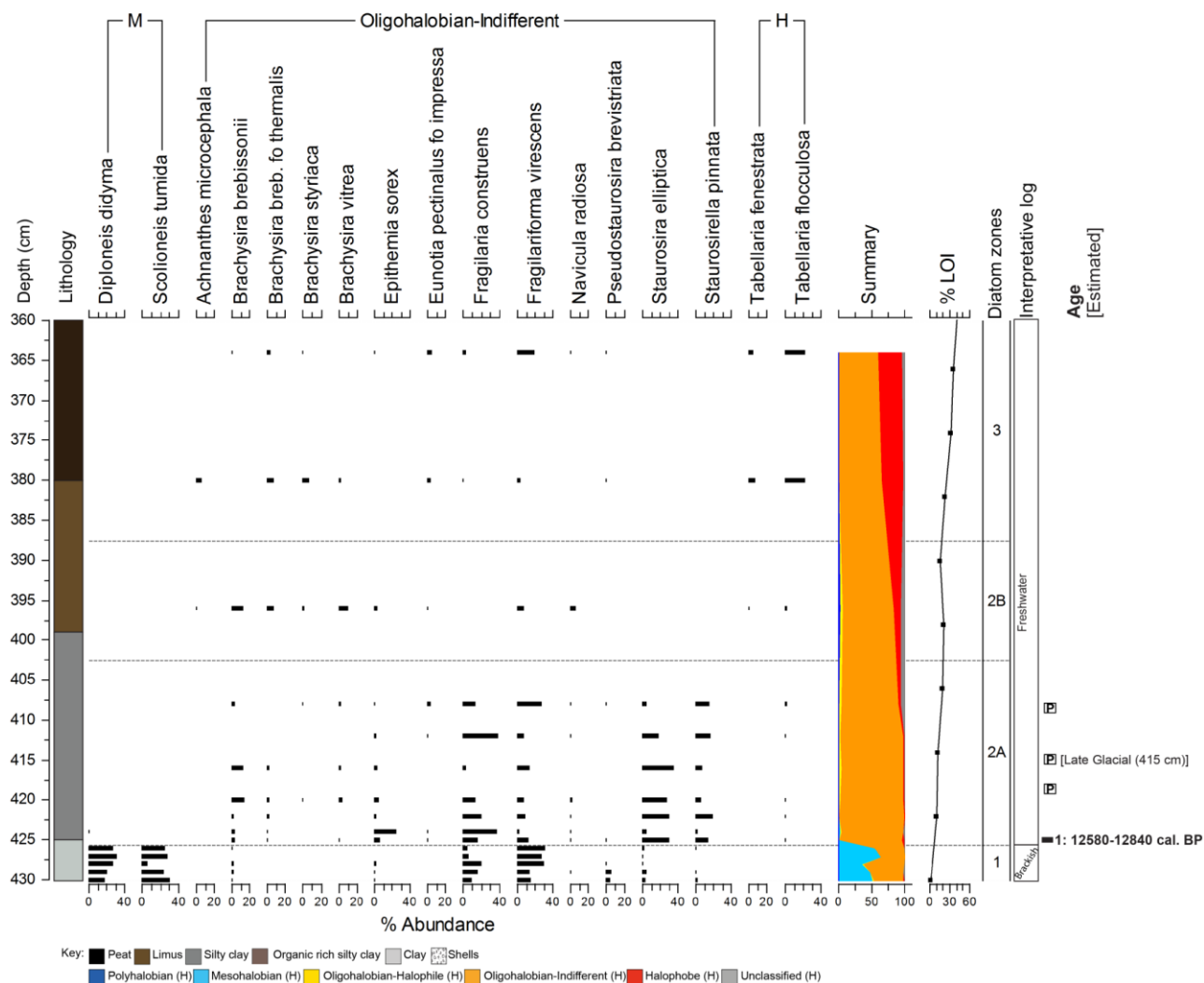
Site (index point ref.)	Laboratory code	Calibrated age (cal. BP)	Altitude (m OD)	Reference Water Level	Indicative Meaning (m OD)	Index point altitude (m OD $\pm$ error)		Tendency	Ref.
Duart Bog (1*)		13400 - 15400	4.76	MHWST	2.1	2.67	0.59	-	This paper
Loch Duart Marsh (2)	Beta-390107	14610 - 15240	1.95	MHWST	2.1	- 0.15	0.59	-	
Loch Duart Marsh (3)	UBA-26501	9890 - 10180	1.95	MHWST	2.1	- 0.15	0.59	+	
Loch Duart Marsh (4)	UBA-26500	310 - 480	1.95	MHWNT	0.9	1.05	1.21	-	
Loch Raas (LR96-4)	AA27222	4354 - 4804	5.09	MHWST + 0.20	2.58	2.52	0.25	-	Shennan et al. (2000)
Loch Raas (LR96-1)	AA27221	4153 - 4834	4.16	MHWST + 0.40	2.78	1.39	0.25	-	
Loch Raas (LR96-8)	AA27223	4575 - 4866	3.62	MHWST + 0.20	2.58	1.05	0.25	-	
Dubh Lochan (DHL96-17)	AA23873	4574 - 4961	3.69	MHWST	2.38	1.32	0.43	-	
Dubh Lochan (DHL96-17)	AA23874	5913 - 6192	3.69	MHWNT + 0.80	1.93	1.77	0.43	-	
Dubh Lochan (DHL96-17)	CAM38852	8135 - 8370	3.69	MHWNT + 0.40	1.53	2.17	0.43	+	
Dubh Lochan (DHL96-17)	AA23875	9661 - 10030	3.69	> HAT	2.97	0.72	0.52	L	
Badentarbat	SRR5485	5652 - 5910	0.9	MTL	0.23	0.67	1.50	-	



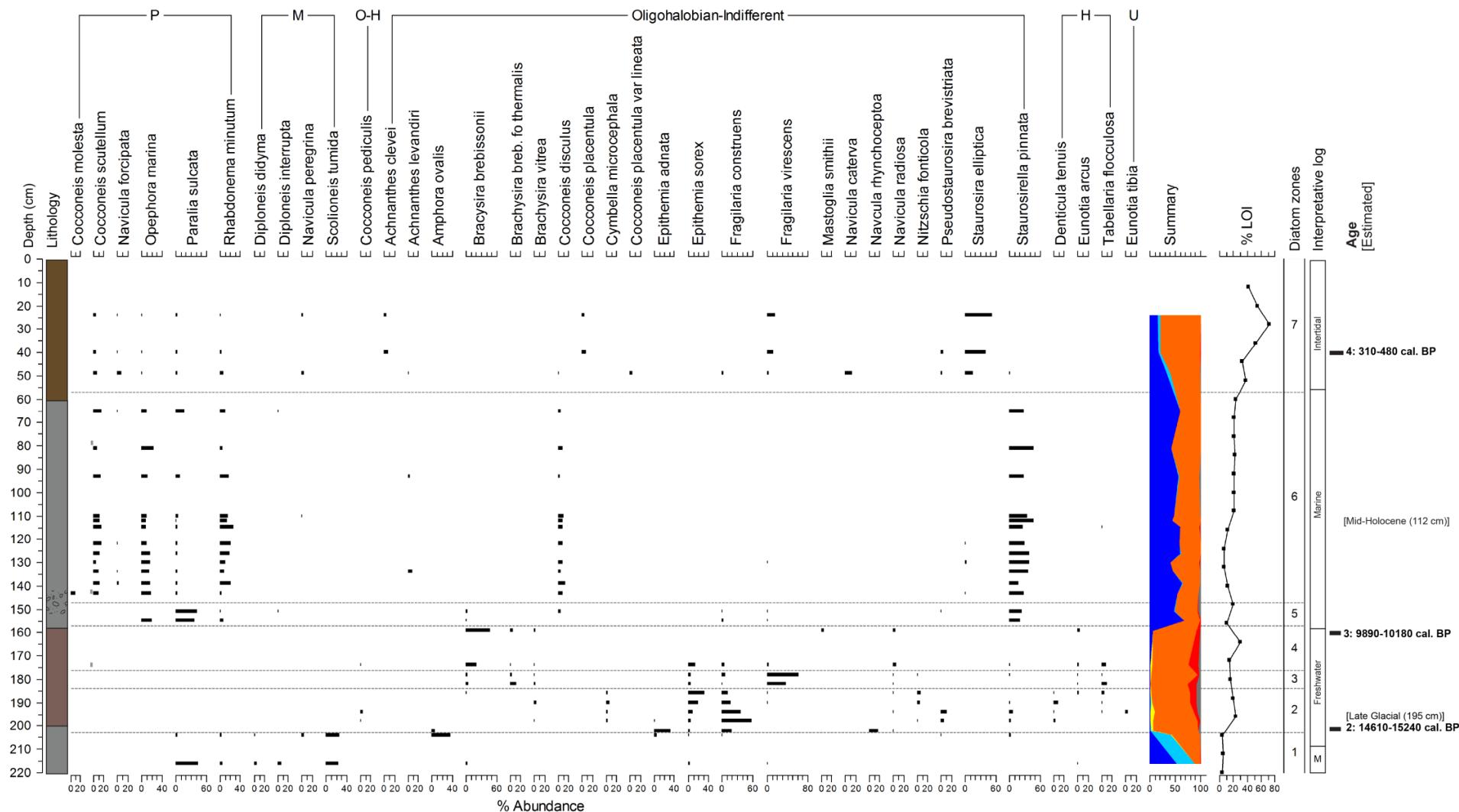




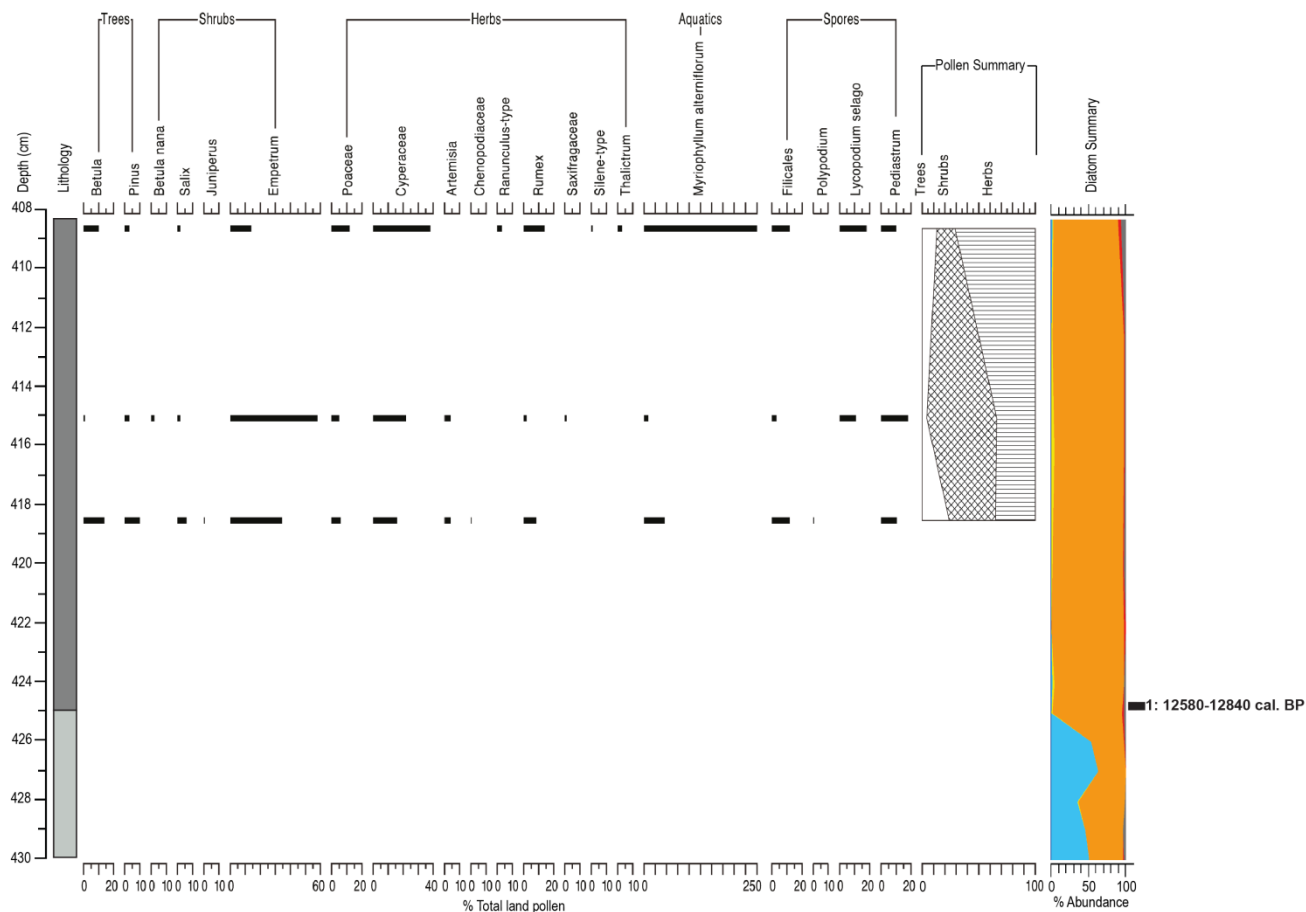
**Figure 2:** Published sea-level index points from Dubh Lochan (DL; isolation basin), Loch Raa (LR; tidal marsh) and Badentarbet (B; wetland and barrier) in the Coigach area of Assynt (adapted from Shennan et al. (2000)). The arrows indicate the positive or negative tendency associated with each sea-level index point whilst the limiting index point is denoted by a black square symbol.



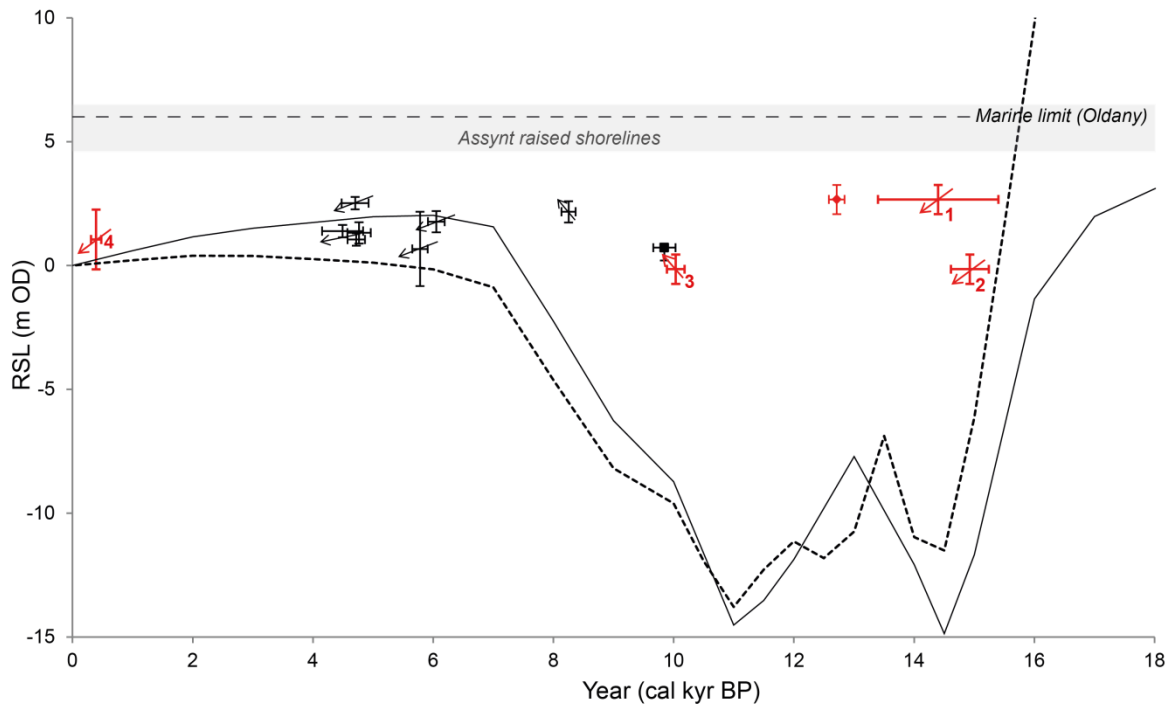
**Figure 3:** Summary diatom flora, lithostratigraphy and diatom assemblage (flora shown exceed 5 % of total valves counted) for Duart Bog (core DuB-13-3), illustrating the transition from brackish-dominant to freshwater conditions between zone 1 and 2A. The position and calibrated age of radiocarbon dates are shown as well as the age indicated by the supporting pollen analysis (shown by the P) (Figure 5).



**Figure 4:** Summary diatom flora, lithostratigraphy (see Figure 3 for key), and diatom assemblage (flora shown exceed 5 % of total valves counted) for Loch Duart Marsh (core LDM-13-1), illustrating the transition from marine to freshwater conditions between zone 1 and 2 and zone 4 and 5. The position and calibrated age of radiocarbon dates are shown as well as the age indicated by the supporting pollen analysis (Supplementary Table 1).



**Figure 5:** Summary pollen and diatom flora, lithostratigraphy (see Figure 3 for key), pollen assemblage and calibrated radiocarbon date for Duart Bog (core DuB-13-3).



**Figure 6:** Bradley et al. (2011) (solid line) and Kuchar et al. (2012) (dashed line) model predictions for Assynt, including previous sea-level index points for the Assynt region from Coigach (Shennan et al. 2000), shown in black, and from Duart (this study), in red. Index point 1 (DuB-13-3) based on radiocarbon material is denoted by the red diamond symbol whilst limiting index points are denoted by a black square. The arrows indicate the positive or negative tendency associated with each sea-level index point; increasing arrow indicates RSL increase for example.

# **Late Glacial to Holocene relative sea level change in Assynt, northwest Scotland, UK**

Hamilton, C.A., Lloyd, J.M., Barlow, N.B., Innes, J.B., Flecker, R., Thomas, C.P.

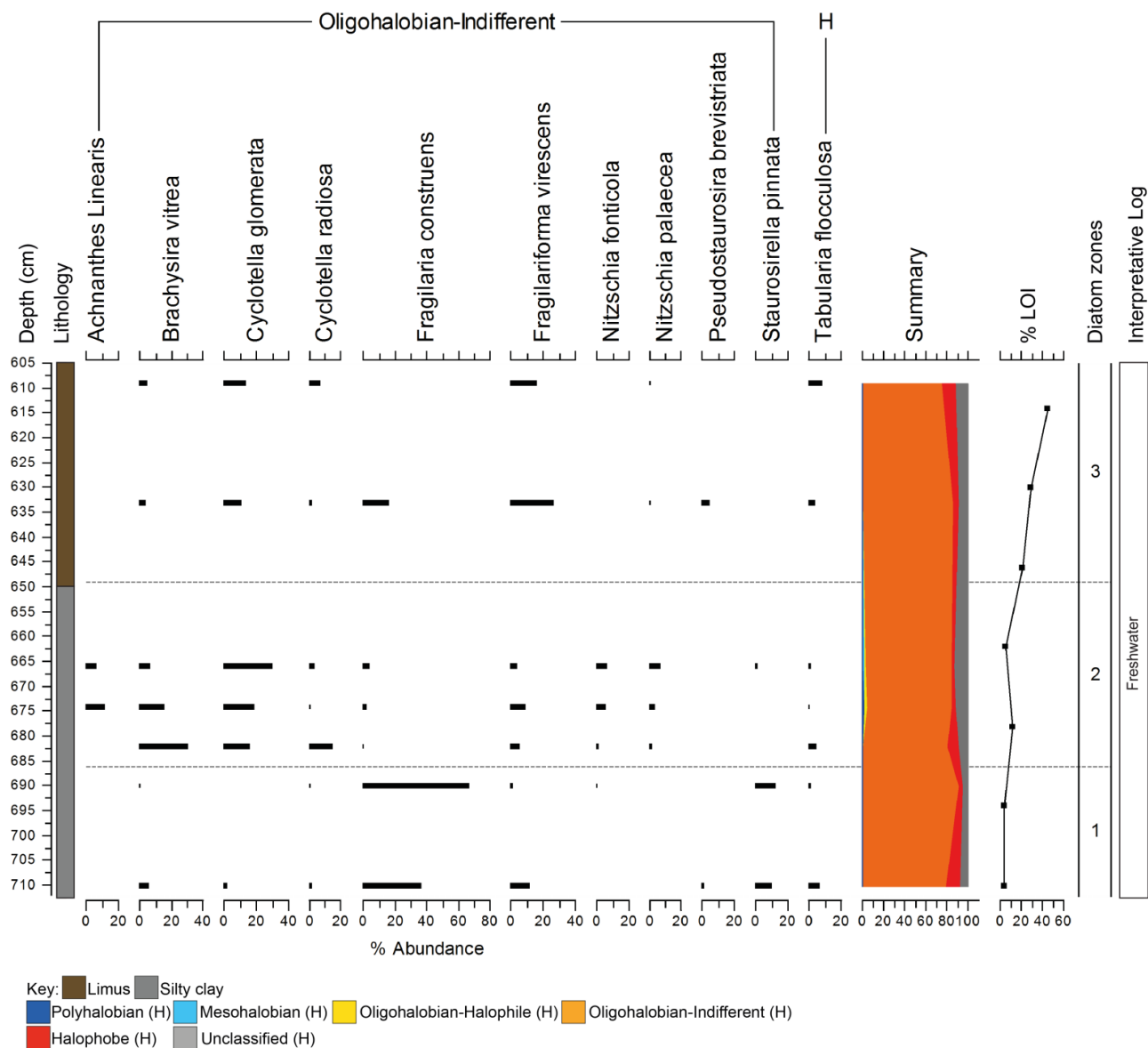
Quaternary Research, 2015

## **Supplementary Information**

<b>Supplementary Table 1</b>	Qualitative pollen counts to support AMS <sup>14</sup> C radiocarbon dates from Loch Duart Marsh core (LDM-13-1).
<b>Supplementary Figure 1</b>	Summary diatom flora, lithostratigraphy and diatom assemblage (flora shown exceed 5 % of total valves counted) for Oldany, illustrating the freshwater conditions.
<b>Supplementary Figure 2</b>	Correlation of pollen zones at sites, including Duart, in northwest Scotland between the Late Glacial Interstadial and Early Holocene. Dominant pollen types are listed for each zone whilst those in brackets are less abundant, however characteristic of the zone. Calibrated radiocarbon dates are positioned at the appropriate zone boundary. Site locations are shown in the inset map.

Supplementary Table 1

Pollen	Depth (cm)	
	112	195
<b>Land pollen</b>		
<i>Betula</i>	27	0
<i>Alnus</i>	14	0
<i>Quercus</i>	3	0
<i>Ulmus</i>	1	0
<i>Corylus</i>	6	0
<i>Pinus</i>	1	0
<i>Salix</i>	1	0
<i>Calluna</i>	1	0
Cyperaceae	3	1
Poaceae	1	5
Cruciferae	1	1
<i>Plantago maritima</i>	7	7
<i>Rumex</i>	0	5
<i>Artemisia</i>	0	2
<i>Empetrum</i>	0	1
Labiatae	0	1
<i>Equisetum</i>	0	1
<b>Algae and Freshwater Aquatics</b>		
<i>Pediastrum</i>	0	21
<i>Myriophyllum alterniflorum</i>	0	130
<i>Botryococcus</i>	0	45
<i>Debarya</i>	0	1
<b>Indicated Environment</b>		
	Mid-Holocene wooded with saltmarsh indicators (coastal)	Lateglacial arctic tundra with open, cold water (deep pond)



**Supplementary Figure 1**



